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Leptonic Photons and Nucleosynthesis

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Abstract

Should $U(1)$ long-range forces be associated to electron, muon and/or tau quantum number then their "fine structure constants" are seen to be bound by nucleosynthesis data to be less than about 1.7×10^{-11}. For τ and μ this is the best upper limit up to date.

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While the rôle of electric charge, weak isospin, and color is completely clarified in the modern Particle Physics paradigm, i.e. they are sources of interactions linked to local gauge invariance, this is not the case for lepton and/or baryon number. Apparently, lepton (and baryon) number conservation holds to an extremely high degree and no violation has been experimentally established so far. Yet no forces associated to these quantum numbers have been identified, a fact that clearly distinguishes them from, say, electric charge. The question whether baryon/lepton number are charges like electric charge or color (i.e. which can be associated to forces that feel such charges) has already a long tradition in Particle Physics. It was first raised by Lee and Yang [1] who pointed out that the existence of these forces would spoil the equality of gravitational and inertial mass. Very recently, Okun [2] has reexamined the whole issue of long-range forces associated to electron, muon, and tau lepton number. He considers the existence of new massless U(1) vector bosons coupled to those charges, considered as independently conserved quantities. He analyses the various phenomenological consequences of their presence and states the corresponding limits on the associated "fine structure constants", α_e, α_μ, and α_τ.

The properties of the tau lepton doublet are in general the less precisely known among leptons and this turns out to be also the case for the issue discussed here. Indeed, as Okun states in his paper [2], there are no direct laboratory upper limits on α_τ and the limit on α_μ ($\alpha_\mu < 10^{-5}$) is much worse than $\alpha_e < 10^{-49}$ for the first generation, derived from Dicke's experimental limit on the equivalence between inertia and gravity. In the present paper we fill this void and provide a bound on α_τ and α_μ. We find $\alpha_{\tau,\mu} < 1.7 \times 10^{-11}$. These limits are obtained from the nucleosynthesis constraint on extra effective massless degrees of freedom and are much better than the laboratory limits stated above, especially for the tau lepton. Since we consider electron, muon, and tau lepton number as independent charges, our results are valid for either one of them. For ease of presentation, however, we shall in what follows only refer to the tau family.

Results on constraints derived from nucleosynthesis are frequently presented in terms of how many equivalent massless neutrino species do data on helium-4 and other light element abundances actually allow. A very recent reanalysis of this question fixes this maximum number to be very safely four [3]. Therefore, at most one extra equivalent neutrino species can be accomodated. Adding one τ-photon (γ_τ), and the right-handed ν_τ -also in equilibrium because of the vector character of the hypothesized new interaction- would clearly exceed this limit. Thus, τ-photons should be decoupled for $T \sim O(1)$ MeV, the neutrino decoupling temperature.

Let us see the implication for the problem at hand. Decoupling of a species occurs whenever the Hubble expansion rate overcomes the annihilation rate for this species. The cross-section for $\gamma_\tau \gamma_\tau \to \nu_\tau \nu_\tau$, in the C.M., is

$$\sigma = \frac{2\pi\alpha_\tau^2}{s} \left(\log \frac{s}{k_D^2} - 1 \right) , \tag{1}$$

where s is the C.M. energy squared and k_D is the Debye momentum, i.e.

the cut-off in momentum corresponding to the physical screening of the interaction range by the τ-charges of the neutrino-antineutrino plasma. It is explicitly given by,

$$k_D^2 = \frac{\alpha_\tau n(\nu)}{T} \tag{2}$$

with $n(\nu)$ the number density of neutrinos.

The relevant interaction rate is

$$\Gamma = n(\gamma_\tau) < \sigma v > \tag{3}$$

where the cross-section is thermalised and $n(\gamma_\tau)$ stands for the γ_τ number density. A fairly good numerical approximation for it is

$$\Gamma = 0.053\, \alpha_\tau^2\, T\, \log \frac{160}{\alpha_\tau} \tag{4}$$

On the other hand, the Hubble expansion rate is

$$H = \sqrt{\frac{4\pi^3}{45}}\, g_*^{1/2}\, \frac{T^2}{M_{Pl}} \tag{5}$$

with $g_*(T)$ the number of effective degrees of freedom at temperature T.

As a consequence of the T dependence in Eqs. (4) and (5), if at a certain T τ-photons are in equilibrium with neutrinos, they will remain in equilibrium for any temperature below T [1]. Therefore, since for $T \sim O(1)$ MeV τ-photons should be already frozen out, they were never before in equilibrium with the ordinary relativistic plasma. We are forced to require that equilibrium sets in for $T < 1$ MeV. This requirement then leads to

$$\alpha_\tau \leq 1.7 \times 10^{-11} \tag{6}$$

by equaling Eqs. (4) and (5) at $T = 1$ MeV. A larger α_τ would imply equilibrium at $T > 1$ MeV which is forbidden by observation. Below this temperature, τ-photons and neutrinos share the same temperature, their wavelengths redshifting with the expansion so that, at present, τ-photons would contribute a fraction of the total neutrino energy density.

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[1] Note that this is opposite to what happens with ordinary weak interactions.

References

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